

GRAVITAS: Portraits of a Universe in Motion

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ABSTRACT

GRAVITAS is a self-published DVD that presents a visual and musical celebration of the beauty in a dynamic universe driven by gravity. Animations from supercomputer simulations of forming galaxies, star clusters, galaxy clusters, and galaxy interactions are presented as moving portraits of cosmic evolution. Billions of years of complex gravitational choreography are presented in 9 animations - each one interpreted with an original musical composition inspired by the exquisite movements of gravity. The result is an emotive and spiritually uplifting synthesis of science and art.

The GRAVITAS DVD has been out for two years now but I am now making the DVD disk image freely available for personal and educational use through a bittorrent download. Download and burn at your leisure. The animations are also downloadable in various video formats. Follow the various links through the home website <http://www.galaxydynamics.org/gravitas.html>

The liner notes of the DVD and track descriptions follow.

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1. Understanding the Dynamic Universe

When we look with wonder at galaxies in the beautiful images from space, we immediately perceive that these vast systems of stars are in motion. The spiral patterns of galaxies intuitively suggest a system in rotation. We have all seen the spiral vortices of water going down the drain or similar patterns in cream stirred into a cup of coffee. The distorted forms of close pairs of galaxies with their long tails and interconnecting bridges of stars are not as intuitive but do suggest that these systems are interacting in a strong and violent way. We now know that these complex patterns are manifestations of the long reach of gravity generated by the stars, gas and dark matter that make up the galaxies. Unfortunately, we cannot witness the dynamics of galaxies directly since the rotational times are typically hundreds of millions of years, much longer than our hundred-year life spans. Galaxies therefore appear as still-lives to us - incredibly beautiful images - but frozen snapshots presenting single frames from a series of prolonged cosmic dramas.

The 9 computer animations presented on this DVD bring life to the snapshots of galaxies and present the universe as a place that is in constant motion, a place that is evolving and changing in complex ways over billions of years. Each animation is a celebration of gravity acting in its purest form through Newton's laws of motion. While Einstein usually gets most of the credit for linking gravity to the larger universe, Newton's laws still reign supreme for describing most of the behaviour in the solar system, star clusters, galaxies and even bigger things like galaxy clusters and the large-scale structure. Small, high-density objects such as neutron stars and blackholes and the biggest thing we know, the universe seen as a whole, require Einstein's detailed formulation of gravity in his Theory of General Relativity. The phenomena of everything in between these two length scales can be described very well by the methods of good old fashioned Newtonian gravity.

The study of the motion of stars in clusters, galaxies and the large-scale universe is known as stellar or galactic dynamics. The underlying description is Newton's N-body problem: the computation of the motion of "N" (a large number) bodies (e.g. planets or stars) each of which is pulling and being pulled by every other body through the force of gravity. The force between bodies is inversely proportional to square of the distance between them. Newton's great triumph was the discovery of an exact solution of the two-body problem for the inverse-square force law that predicted that planets should move on Keplerian elliptical orbits. However, for N greater than two the problem had no general solution. In the pre-computer era, this problem was virtually intractable because of the large amount of computing needed even for small systems of bodies. Only complex perturbation calculations could be done to understand the subtleties of the deviation from elliptical orbits of the inner planets due to the gravitational effects of Jupiter and Saturn.

For a long time, the solar system was the only part of the universe that was seen as dynamic and studied in detail with Newton's physics. However, as telescopic observations expanded our view of the universe it became clear that larger systems of gravitating bodies also occurred in nature. Star clusters containing hundreds and even as many as a million stars in globular clusters were commonly observed. And finally astronomers realized that the great spiral nebulae were actually large systems of stars often laid out in a disk like the Milky Way but at such great distances that the combined light of their stars appeared as a nebulous haze. These systems contained hundreds of billions of stars and were configured as disks - much like the layout of the solar system - and were spinning slowly in space.

A typical galaxy is one hundred thousand light years across with a mass of one hundred billion suns implying rotational periods of hundreds of millions of years - timescales so long that their spinning motions could never be perceived in a human life span. Computing the motion of the 9 planets in the solar system was hard enough. How could one possibly deal with one hundred billion stars?

In the pre-dawn light of the computer era, the Swedish astronomer Erik Holmberg performed a remarkable experiment to explore the gravitational dynamics of interacting galaxies. On a table top, he laid out two disk configurations of 37 light bulbs, each one representing a spiral galaxy. Light acted as a proxy for mass. Since the intensity of light falls off as the inverse square of distance, the combined intensity of light measured by a photocell placed at the position of a light bulb would be proportional to the equivalent force of gravity. In this way, he meticulously measured the "force" at the position of each light bulb which allowed him to calculate the change in position according to Newton's laws and so solve the N-body problem. By carefully moving the light bulbs according to this calculation in a series of steps, he was able to follow the motion of this 74 particle system. He showed that interacting galaxies could excite spiral structures. The first studies in computational galactic dynamics had begun.

By the sixties, electronic computers became widely available to scientists and early pioneers most notably Sverre Aarseth made a first hard attack at numerical computation of the N-body problem modeling systems with a few hundred particles. By the early seventies, the Brothers Toomre presented a detailed collection of N-body calculations with accompanying elegantly drafted drawings clearly illustrating that gravity was responsible for the phenomenology of the tails and bridges in real interacting systems of galaxies. As computers grew in power through the seventies and onward to the end of the century, a variety of new efficient methods were developed for computing the N-body problem to study the detailed dynamics of galaxies and the growth of structure in the universe. The beautiful animation of the merger of a small group of spiral galaxies created by Joshua Barnes in the early nineties

using the tree algorithm invented with Piet Hut led the way inspiring further intense efforts to visualize galactic dynamics.

As we begin the 21st century, the methods for computing the N-body problem have grown greatly in computational efficiency and have been adapted to work on parallel supercomputers: vast arrays of thousands of computational nodes interconnected with a high speed network. Calculations using tens to hundreds of millions of particles are now routine and the animations presented here are derived from simulations of this size. There are now some calculations being done with as many as 10 billion particles! In a few short years, it will be possible to compute the N-body problem in a Galactic model containing as many particles as there are stars! This is a truly amazing advance when looking back at Holmberg’s heroic effort with 74 light bulbs.

The animations that I present here descend directly from this legacy of hard work and ingenuity fueled by the desperate need to understand and see the working machinery of nature at the largest scale. They build upon the astrophysical knowledge and technical skills of many researchers over the past few decades. Astronomers are driven to desperate acts by their insatiable curiosity and voyeuristic tendencies. They want to know and they like to watch. I hope you do too!

2. Track Descriptions

2.1. Cosmic Cruise (1:55)

About 14 billion years ago, the universe began in a Big Bang. In one single instant, all matter and energy were created. Rapid expansion caused the matter to cool and change into atoms and also the mysterious dark matter. At first, the dark matter was spread out evenly but faint echoes of the seething quantum foam that existed at the instant of creation remained like random ripples on the surface of a frozen pond. Gravity took hold of these noisy echoes and caused them to collapse into halos of dark matter that became the seeds of the galaxies.

In this animation, we fly straight through a 130 million particle simulation of dark matter travelling hundreds of millions light years over 14 billion years. We illuminate the dark matter particles so that we can watch the formation of the cosmic web - the foundation of all structure in the prevailing model of cosmology. At the start, the regular grid of particles reflects the featureless nature of the universe at the beginning. As the flight continues, we witness the formation of the first structures through the collapse of density fluctuations. These merge with other structures and grow into the dark halos of sizes varying from galaxies

to galaxy clusters.

2.2. Galactic Encounters (3:11)

The dark matter provides the framework for the universe but what we see are the galaxies - vast islands of stars and gas that form at the centre of the dark halos. The galaxies themselves can gather into enormous clusters with hundreds and even thousands of members. There is little breathing room for a galaxy in a cluster and soon strong interactions and collisions ensue as the galaxies fall together. Galaxies are diaphanous objects - puffs of smoke easily torn apart by the forces of gravity and many merge together into an amorphous central blob of stars while others are left severely damaged.

Here we watch a hundred galaxies fall together into a forming cluster. Our perspective is from a starship flying into the cluster starting several million light years away and cruising to within a hundred thousand light years of the giant elliptical galaxy forming at the cluster centre. As we fly through, we observe the merging and tidal disruption of many spiral galaxies as they orbit within the cluster. Ten billion years elapses within about 3 minutes so time passes at a rate of 50 million years per second!

2.3. Swarm (2:14)

By increasing the playback speed, we get a different impression of the dynamical processes in clusters. Here we look at the cluster from the previous track again but from 3 different fixed perspectives and also speed up the playback to 200 million years per second. The cluster dynamics take on a violent and frenzied character in stark contrast to our usual impressions of stately slow changes from astronomical imagery.

2.4. Nightfall (5:55)

Not so long after the Big Bang, somewhere in the universe the first star was born. Great clouds of gas condensing within the galaxies were stellar cradles. The largest clouds condensed into globules that flared into millions of stars and became globular clusters. These ancient families are fossils of the first moments of creation and shine mainly today by the light of red and blue giants. For billions of years, the stars have moved on their way rarely encountering their companions shuttling back and forth indifferently guided by the relentless force of gravity.

This animation is inspired by the classic Isaac Asimov short story Nightfall written in Astounding Stories in 1941. There an astronomer on a planet with multiple suns where it is always day learns through his N-body calculations that all of the suns will soon set for the first time in thousands of years. The last time this happened civilization collapsed because of the mass insanity that followed when night fell. As the last sun sets and mass hysteria ensues, the astronomer looks up into the sky and perceives the fantastic view of a sky filled with tens of thousands of stars for he lives on a planet at the heart of a globular cluster! I have visualized the stars in the animation to reflect the true colour and brightness distribution in globular clusters and reproduce the look of Hubble Space Telescope images of globular star clusters accurately.

2.5. Klemperers Dream (4:03)

Nature provides us with random acts of gravitational violence in the form of galaxy collisions. Graceful spiral forms, tails and bridges are sculpted by these interactions. But we know how gravity works and galaxies are structured, so we can take the sculptors tool from Natures hand and play with it in a supercomputer removing the random element.

Klemperer found that special symmetric arrangements of particles could follow predictable orbits. These exact N-body solutions seem to have no natural counterpart and even Klemperer stated that he really just studied them for fun! In the same spirit, I have put galaxies in similar unnatural symmetric configurations to explore their evolution. One amazing consequence of Newtons laws of motion is that any system with some symmetry built in should preserve that symmetry even if complex dynamical behaviour is occurring. For the sequence of simulations here, it seems that symmetry is preserved even when spiral patterns emerge after the galaxies interact strongly. But by the end of each sequence, the symmetry is lost. So is Newton wrong afterall? No! These nonlinear dynamical systems are unstable and become chaotic. Tiny deviations introduced by computer imprecision are eventually amplified and lead the system away from symmetry. So these simulations are not just for fun after all. They are an interesting illustration of the emergence of chaos in nonlinear dynamical systems.

2.6. Spiral Metamorphosis (6:18) / Future Sky (6:37)

The harsh reality of the distant universe with all of its violent interactions seems remote from our human existence and all might seem to be quiet and normal in our home the Milky

Way. But it seems likely that in a mere 3 billion years, our neighbouring galaxy Andromeda and the Milky Way will fall together and have a close collision. They will likely merge and be reborn as a single giant elliptical galaxy over the course of another billion years or so. How might this metamorphosis play out and what might you see if you looked up at night over the next 4 billion years! The space between stars is so vast compared to their size that during a galaxy collision no individual stars actually collide with one another. So our sun and its family of planets will be taking a passive but exciting ride through the pair of coalescing galaxies and take on a spectacular view of the unfolding disaster in relative safety.

I have set up a model system of colliding galaxies that reflects the current state of our the Milky Way and Andromeda system. There are still some uncertainties about the exact trajectories and masses of the two galaxies but I have set up a plausible case where they fall together and collide almost directly passing within 60000 light years of each other. Also, I only present the view of the naked stars unobscured by the interstellar gas and dust clouds within the galaxy.

We get a chance to see it all from 4 perspectives: two fixed positions in space a million light years away (Spiral Metamorphosis) and two sky views, the first that projects the full 360 degrees of the sky onto an oval map and the second a view of one hemispheric dome of the night sky. In the sky views (Future Sky), one particle is identified as the sun within the model of the Milky Way and our view is always from this perspective with our attention directed towards the central bulge of the Galaxy making for a mind boggling spectacle.

The view from far reveals an exquisite ballet of mutual annihilation and transformation into an elliptical galaxy. The Milky Way is seen coming in from the bottom in a face-on and edge-on view. After the interaction, long tidal tails of stars are flung out in open spiral patterns from both galaxies by the strong gravitational tides during the interaction. While separating, the two galaxies develop detailed spiral structure and then fall back for a second collision finally to merge. The mutual annihilation of the two galaxies leads to a big splash showing up as a complicated system of loops and ripples that represent turning points of stellar orbits. The two galaxies finally settle down into a single elliptical galaxy surrounded by remnant debris of their violent interaction.

In the sky views, the arch of the Milky Way is apparent at first as a band of stars and tiny Andromeda is seen scrolling past beneath the arch but slowly growing in size as it approaches. When the 2 galaxies intersect, the sun is flung out far from the colliding pair of galaxies and our view oscillates between a remote view of events to a wild ride right through the centre of the galactic bulge! The orbit of the sun is no longer circular but now follows a convoluted pattern with the distorted gravitational field of the merging galaxies. A final look back from the far flung sun shows the final merger of the two galaxies.

2.7. Galaxies in Collision (7:53)

We revisit the galaxy cluster simulations of Swarm followed by random views of two-galaxy collisions. The animation begins slowly to allow an appreciation of the grace of gravitational dynamics but the tempo gradually increases to change the impression to a frenetic dance of severe intensity and violence. The animation ends with a fireworks display of rapid fire merging pairs of galaxies fading into the Hubble Space Telescope image of the Mice one of the well-known nearby famous pairs of interacting galaxies. The final image reminds us that we live in one single instant of an evolving universe.

2.8. Metamorphosis 3-D (6:13)

I have re-run the simulation of Spiral Metamorphosis using stereoscopic rendering methods to produce a red-blue 3-D animation. To appreciate this animation, put on the 3-D glasses (red lens over your left eye) and seat yourself in direct line with the centre of the screen at a distance of about 5 times the width of your screen. Relax your eyes and watch a 3-dimensional rendition of the merger of the Milky Way and Andromeda from 3 different perspectives! In 3-D, the patterns of shells and ripples take on a completely different light and reveal the amazing depths of complexity in the dynamics of galaxies.

3. About the Music

An essential component of this compilation of animations is the music of composer-pianist John Kameel Farah. He draws upon and synthesizes the sound-worlds of renaissance and baroque counterpoint, free improvisation, Middle-Eastern music, ambient minimalism, techno and electronica to create a music that crosses time and dimension. His creative efforts are fueled by exchanges of physical, spiritual and emotional energies, on both a macro-cosmic and microscopic level. The accompanying compositions are direct musical interpretations of the unfolding dynamics presented in each animation. The music provides a wondrous ambience and serene state of mind that permits us to contemplate the beauty of a universe in motion. For more information on concerts, recordings and projects, please visit www.johnfarah.com.

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